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Identification of spatial and temporal patterns of Australian daily rainfall under a changing climate

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Abstract: Rainfall is a highly variable component of the climate system. There are substantial spatial and temporal variations in the frequency and spatial distribution of rainfall events. Little attention has been paid to the slow but ongoing variations of the spatial patterns of daily rainfall, especially over broad spatial scales. A better understanding of these variations and their long term trends would reduce uncertainty in environmental and natural resource models and improve assessment of ongoing climate change. This study examined the spatial cross-correlations of daily rainfall at 2322 high quality long run rainfall stations across Australia from 1910 to 2011, and assessed their spatial and temporal patterns. It was found that: 1) There has been a long term continuous strengthening in the spatial cross-correlation of daily rainfall across Australia over this period. Most of this strengthening has occurred since the 1970s; 2) The strengthening is more consistent in winter and spring but has occurred in all four seasons; 3) Southeastern Australia has had the most stable strengthening pattern over a broader spatial scale; 4) The strengthening suggests an increase in the broad scale coherence of daily rainfall, such as found in frontal rainfall; 5) These findings are consistent with recent reported changes in synoptic scale climatic driving processes, especially the increasing frequency of frontal systems and the decreasing frequency of storm events in the Australian region. An increase in the broad scale coherence of rainfall is likely to improve the accuracy of daily rainfall interpolation and influence dependent hydrological modelling. Interactions of data quality with the derived correlation patterns are also discussed.

Keywords: daily rainfall; spatial cross correlation; rainfall temporal and spatial patterns; fronts; climate change

1. INTRODUCTION

Australia is a relatively dry continent and rainfall is perhaps the most important meteorological parameter affecting Australia's economic and social activities (Weymouth et al. 1999). Consequently, regional knowledge of rainfall, including the daily rainfall, is critical for economic and environmental planning and water resources management. A better understanding of the national and regional spatial patterns of daily rainfall and their long term trends will help to reduce the uncertainty in associated environmental and natural resource models and help to construct more reliable policies for the mediation of the impact of climate change.

There have been many studies of Australian rainfall and its variability, as well the driving processes. Allen and Haylock (1993) linked the observed decrease in winter rainfall over the southwestern portion of Western Australia to a change in the longwave pattern of mean sea level pressure and therefore a modulation of frontal activity in this region. They suggested that low frequency fluctuations in the El Niño-Southern Oscillation (ENSO) may have played a major role in this process. Hopkins and Holland (1997) identified a trend toward increasing frequency of Australian east coast cyclones during 1958 to 1992, but that the number of local convective heavy-rain events had decreased over the period, especially in the higher latitudes. Nicholls et al. (1997a) found that Australian rainfall was more variable than could be expected from similar climates elsewhere in the world. Hennessy et al. (1999) found that strong correlations existed between interannual variations in temperature, total rainfall, heavy rainfall and the number of rain days. A study by Haylock and Nicholls (2000) detected a decrease in the number and intensity of extreme rainfall events in southwest Western Australia and an increase in the proportion of total rainfall from extreme events in eastern Australia during 1910 and 1998. Hope et al. (2006) found that the frequency of the troughs associated with wet conditions across southwest Western Australian has declined markedly since 1975 while the frequency of the winter circulations with high pressure over the continent, associated with dry conditions, has increased. Risbey et al. (2009b) concluded that the key large-scale driver of rainfall variability in the Australian region was the El Niño–Southern Oscillation (ENSO).

Most interestingly, the frontal rainfall frequency has been increasing over southern Australia over the past 50 years (Berry et al. 2011a & 2001b; Catto et al. 2012). In the meantime, based on observations and climate modelling, Frederiksen et al. (2011) found that there had been fewer rain storms across southern Australia over recent decades due to a reduction in the strength of the mid-latitude jet stream and changes in atmospheric temperatures. In addition, it has been reported that there are fewer tropical cyclone storms across Australian region (Nicholls et al 1997b; Webster et al. 2005; Haig et al. 2014).

While considerable attention has been paid to phenomena such as extreme rainfall events and intensity, less attention has been paid to low temporal frequency rainfall phenomena, such as long term changes in the spatial distribution patterns of daily rainfall events and intensity. Long term changes of daily rainfall patterns are less easy to observe, especially long term changes over broad spatial scales, but a long term change in daily rainfall patterns may have a significant impact on ecosystems and the human environment.

Daily rainfall and its spatial distribution should reflect features of the driving processes. It could therefore be expected that changes in synoptic scale rainfall processes will be reflected in the long term daily rainfall records. While long wave variations of large-scale rainfall processes across Australia have been observed (Allen and Haylock 1993; Hope et al. 2006; Timbal et al. 2006; Berry et al. 2011a & 2001b; Catto et al. 2012), there is still a lack of an integrated spatial and temporal analysis of long term Australian daily rainfall patterns and their long term trends, as extracted from a complete dataset of Australian historical daily rainfall records.

The spatial cross correlation of daily rainfall represents the spatial consistency of the rainfall occurrence and rainfall intensity between stations. The spatial and temporal features of these correlations can reveal spatial and temporal patterns of regional daily rainfall, and may help to uncover the features of synoptic scale climatic driving processes. In this study, we investigate the spatial cross correlations of daily rainfall records from 2322 long run rainfall stations in Australia from 1910 to 2011 collected by the Australian Bureau of Meteorology (BOM). The aim is to extract the spatial and temporal features of these correlations and obtain a more explicit picture of daily rainfall patterns and their long term trends with respect to changes in climate over this period. This may help to quantify the impact of projected climate change on Australian rainfall and reduce uncertainty in rainfall projections for the Australian region.

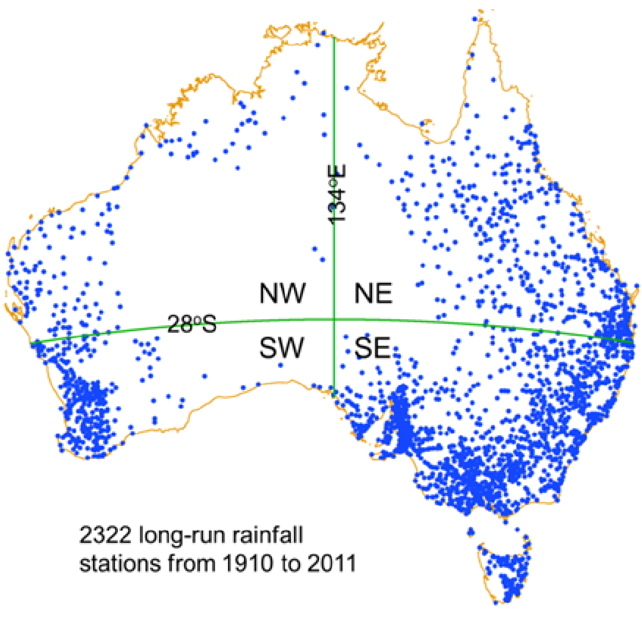

Figure 1. Spatial distributions of 2322 long run rainfall stations in Australia and section division for regional cross correlation analysis. The green lines divide the country into four quadrants for regional analysis

2. SOURCE DATA

2.1. The long run rainfall stations

The total number of rainfall stations in operation each year varies considerably over the period of record. To eliminate a potential influence from changes in the rainfall station network, and ensure an unbiased analysis, A total of 2322 long run rainfall stations for the period from 1910 to 2011 were selected from the national daily rainfall database and were employed for cross correlation analysis (Figure 1). A station was selected from the national dataset if it had daily rainfall data for at least 85 years during the period of 1910 to 2011. On average this group of 2322 stations has 97.4 recorded years per station during 1910 to 2011 and each year those active stations had an average coverage of valid daily rainfall records of 95.8%.

2.2. Further data quality control processing

Having a high quality dataset is critical for achieving a reliable correlation analysis of daily rainfall. There were still considerable errors with the daily rainfall data, particularly errors in the locations of rainfall stations and date shifts of daily records, even though BOM had paid enormous effort to quality control. This study made a substantial effort to further assure the quality of the data. A total of 321 rainfall stations (around 1.8% of all used and live stations) were categorized as un-trusted stations and were dropped from the national database by using a Euclidean distance vs. correlation coefficient rule. Thus, if the daily rainfall records of a rainfall station had very poor correlations with the daily rainfall records of close neighbouring rainfall stations, the rainfall station was inspected and dropped if appropriate.

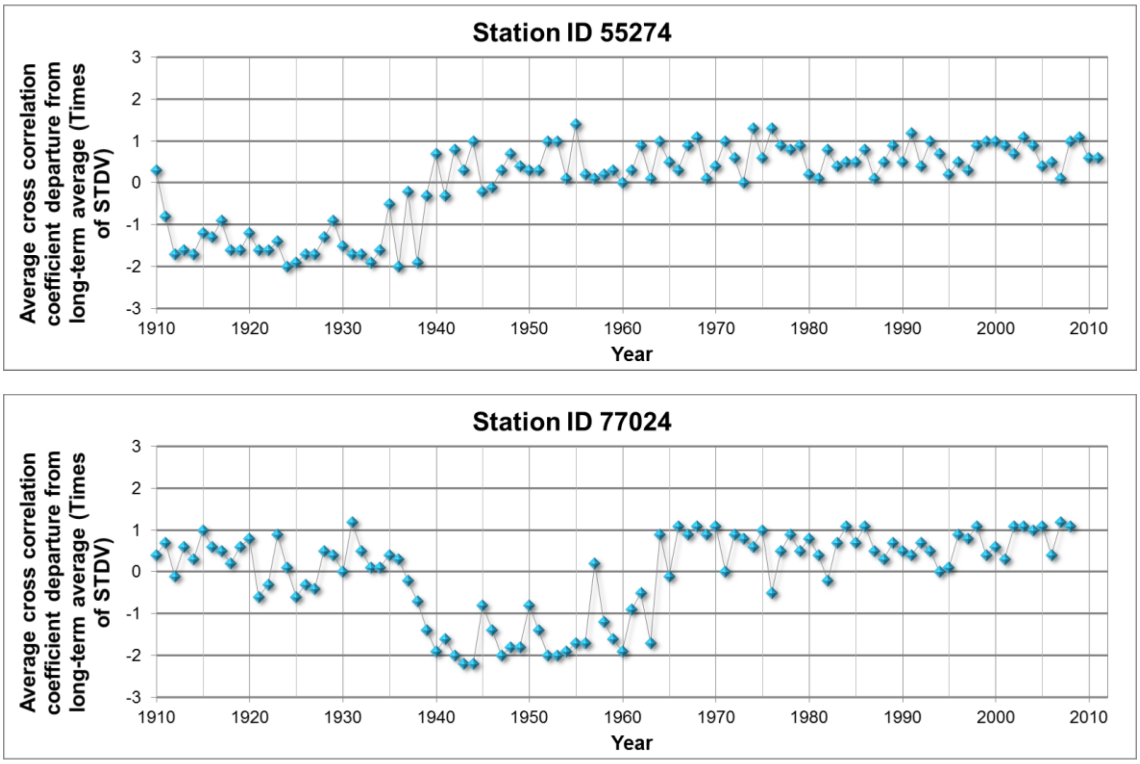

Figure 2. Daily rainfall cross correlations of a given station to its neighbouring stations within a 100km Euclidean Distance radius departure from the long term average.

Date shift errors commonly occur in historical daily rainfall records, with the recorded date of a daily rainfall value typically shifted by one day from its actual date due to various reasons, such as variations in recording practice over the full historical period. A consistent date shift error of daily rainfall records significantly weakens the correlation of a station to its neighbouring stations. The consistency of the variations in cross correlation patterns shown in Figure 2 are very unlikely to have been caused by the time taken by the movement of particular weather systems. This study developed a method to compare the annual cross correlations of a rainfall station to its closest neighbouring stations before and after successive one day shifts were applied to locate the most likely true date. The minimum time coverage for each date shift analysis was one year. It was assumed that date shift errors were not due to random daily recording errors, but due to a consistent error in operational practice. Figure 2 gives two examples where the date shift errors apparently occurred over substantial periods. Thus, stations 55274 and 77027 had consistent date shifts of 28 and 25 years respectively. Figure 3 shows the percentage of stations that had a one day-shift correction for each year among the 2322 long run stations. More than 94% of these errors were an error for which the actual date of daily rainfall record should be adjusted to one day later. It can also be seen from Figure 3 that the date shift errors in the BOM's daily rainfall records has generally decreased over time, with very few date shift errors after the late 1990s. This corresponded with the time of a major upgrade in BoM rainfall data quality assurance practice (Blair Trewin, Private comm.). This confirms that the systematic date shift errors detected in the earlier data are not due to the times taken by the passage of weather systems.

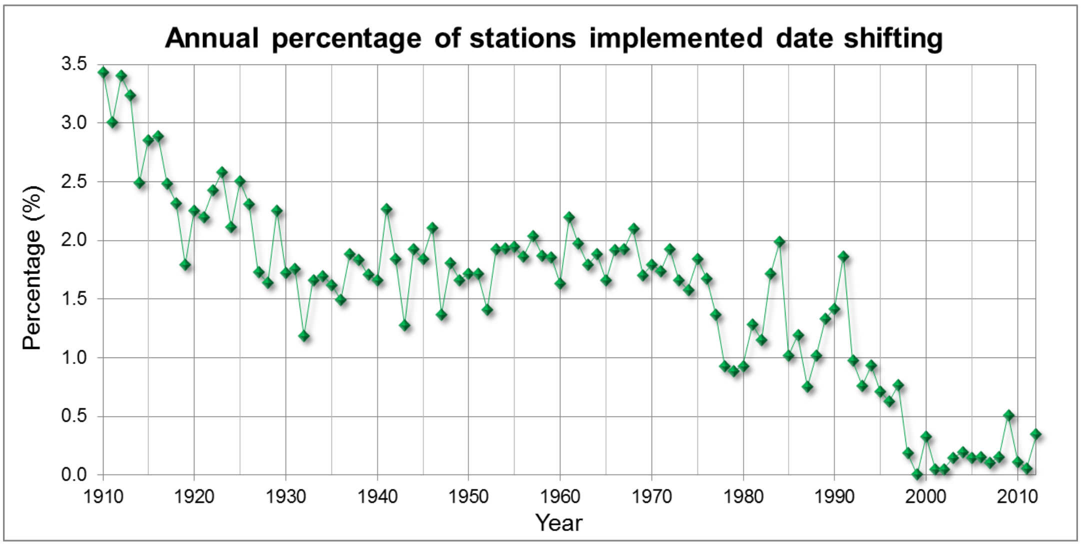

Figure 3. The annual percentage of 2322 long run rainfall stations for which a date shift correction was made.

3. METHODOLOGY AND ANALYSES

The main task of this study was to extract and investigate the spatial and temporal features of the spatial cross correlations of recorded daily rainfall between each pair of rainfall stations at given Euclidean distances and to examine their long term trends.

The calculation of cross correlation coefficients was made in Visual Basic computer programs and implemented within Microsoft ACCESS databases. The coefficients were calculated for each year and the four seasons of the year (DJF, MAM, JJA and SON) from 1910 to 2011 within given Euclidean distances. For each station the search radius for a "neighbouring station" was up to 1000km. The Lambert Conformal Conic projection, which is popularly employed in Australia, was adopted when calculating the Euclidean distance between rainfall stations.

Daily rainfall data typically have a skewed distribution with an overwhelming majority of daily records with value zero. For instance, nearly 79.7% of valid daily rainfall records of those 2322 long run stations were zero during 1910 to 2011. In the desert areas of central and western Australia the percentage of zero records was much higher. There is a potential to yield a distorted and unreliable cross correlation when there are too many zero value records, in particular long continued zero value records, from the correlated stations. In this study, two approaches were taken to reduce the impact of the skewed distribution and zero value records. Firstly, the cross correlation coefficient between each pair of rainfall stations was computed using daily records from those days for which at least one station had a non-zero rainfall record. Secondly, a square root transformation of the daily rainfall data was taken prior to the calculation of cross correlations. The square root transformation can reduce positive skew in recorded daily rainfall values to produce approximately normal distributions, making the analyses more stable and easier to interpret (Hutchinson 1998a, 1998b; Hutchinson and Xu 2013). Here the threshold for a non-zero daily rainfall record was 0.3 mm, which excluded those days with 0.2 mm. A recorded value of 0.2 mm can be ill-defined because of variations in recording practice over the full historical period. For instance, the 0.2 mm record can only be found systematically in BOM's daily rainfall records after 1973.

Thresholds of minimum valid days were set to 30 and 12 respectively for the annual and seasonal cross correlation computations. No cross correlation would be computed for a neighbouring station pair at given period when the number of valid days was below the relevant threshold.

In order to assess the regional characteristics of the cross correlations, annual and seasonal averages and other summary statistics were separately extracted and investigated for four quadrants of the Australian continent. The east west division was given by Longitude 134^{o} E, and the north south division was given by Latitude 28^{o} S (Figure 1). Table 1 lists the number of long run rainfall stations in each quadrant.

National and regional averages of annual and seasonal cross correlations and other statistics were then derived at successive steps of 10 km. The national and regional histograms of those statistics were extracted for each year and for the four seasons.

A search buffer of 10 km was applied to each station to search its neighbours at each given Euclidean distance and then average correlations were calculated. Thus, at a given distance of 100 km, the actual search distance for neighbouring stations was from 95 to 105 km. This ensured that there were sufficient neighbouring stations for each station so that stable and meaningful averages and other statistics could be derived.

Table 1. Number of long run rainfall stations in each quadrant

Northeast	Southeast	Southwest	Northwest	National
480	1396	303	143	2322

4. RESULTS AND DISCUSSION

4.1. Long term trends in the daily cross correlations

The study found that there was a systematic increase in the spatial cross correlations of daily rainfall in Australia from 1910 to 2011, with a marked strengthening of the increase since the mid-1970s, as shown in the trends in the correlations for the 2322 long run stations, at various distances, in Figure 4. The correlations are naturally largest at the shortest distance scale shown (20 km), but the increasing trend in correlation is also evident at the largest distance scale shown (400 km. Larger daily cross correlations indicate an increase in the spatial consistency of daily rainfall events and their intensities. This suggests a general increase in the spatial scale of rainfall events over the country since the mid-1970s.

The broad consistency of the daily rainfall patterns shown in Figure 4 indicates that the changes may not be an isolated phenomenon, but a broad scale indicator of a changing climate system due to broad scale climatic driving forces. It is consistent with observed variations in synoptic scale climatic processes, especially the increasing frequency of frontal systems in Australian region as reported by Berry et al. (2011a & 2001b) and Catto et al. (2012). It also echoes the reported decreasing of storm events in Australian region since decades ago (Nicholls et al 1997b; Webster et al. 2005; Frederiksen et al. 2011; Haig et al. 2014).

Australian rainfall is influenced by synoptic scale phenomena such as ENSO and the Indian Ocean dipole (IOD) that are largely remote from the continent and these climatic drivers modulate the regional spatial rainfall patterns at various temporal scales (Pook et al. 2006; Risbey et al. 2009a). The synoptic scale rainfalls in Australia are mainly driven by extra-tropical weather systems such as fronts and cut-off lows, especially in the southern parts of the country. In particular, the cut-off low and frontal systems are the main driving forces of rainfall during the winter crop growing season (April to October) in southern Australia (Pook et al. 2012). Frontal systems strongly affect day-to-day variability of weather and shape the local space-time distribution of daily rainfall (Evans et al. 2009; Catto et al. 2012; Pink 2013).

Climate change has reshaped atmospheric circulations and other climatic driving forces, and therefore rainfall spatial distribution patterns. Allen and Haylock (1993) reported a modulation of frontal activity in Australian region which might have resulted from fluctuations in the continental anticyclone and semipermanent long wave trough at higher latitudes. Variations in the large-scale atmospheric circulation across southern Australia since 1971 have been reported (Anderson and Garlinge 2000; Frederiksen et al. 2011). It has also been reported that there has been a more frequent than usual passage of lows and fronts over southeastern Australia (Chambers 2003), and as noted above, Berry et al. (2011a & 2001b) have reported an increase in frontal frequency over the past 50 years. Frederiksen et al. (2011) found that there had been a large downturn in the intensity of

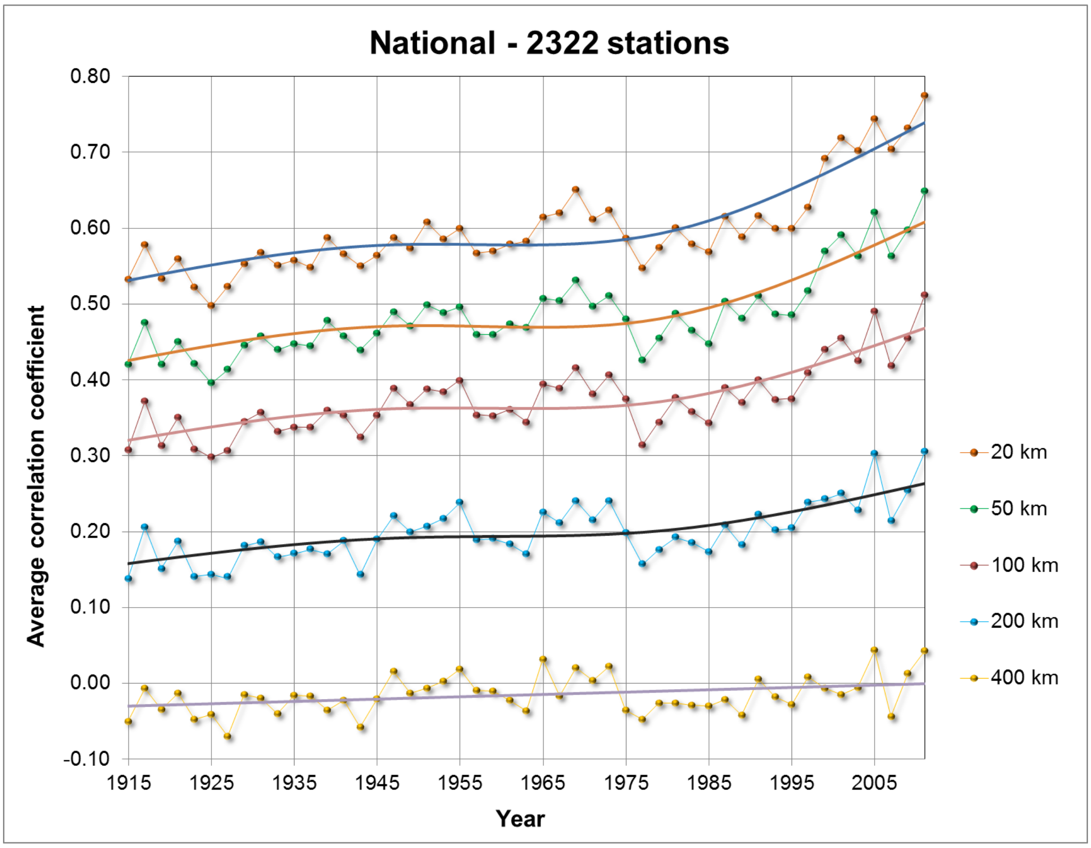

Figure 4. National averages of annual cross correlations from 2322 long run rainfall stations at given 2D Euclidean distances (with smoothing spline trend lines).

storm formations over at least the last three decades compared with the previous three decades due to reductions in the strength of the mid-latitude jet stream and changes in atmospheric temperatures. Their recent work on climate model projections has suggested a continuation of these trends over the next 50 years. The variations in these climatic driving forces have certainly reshaped the spatial and temporal patterns of daily rainfalls in Australia over time. For instance, a frontal rain system will generally produce a widely spread and relatively evenly distributed rain event, while a storm will more likely bring a much localised and unevenly distributed rain event. It appears that the strengthening of spatial cross correlations revealed by this study reflects the reported variations in large-scale climatic driving forces well.

4.2. Regional features of the cross correlations

Regional patterns are generally similar to the national patterns shown in Figure 4 but with some regional differences. The southeast quadrant has the most robust and consistent upward trends of the regional averages of daily cross correlations with the closest similarity to the national patterns. This is to be expected since this quadrant has 1396 out of the total 2322 stations. The large amount of long run stations in this quadrant does help to reduce the year to year fluctuation and smooth the regional averages. The northeast quadrant, with 480 stations, also shows relatively stable increasing trends of regional averages of daily cross correlations similar to the national patterns, but with larger year to year variations than the southeast quadrant. The southwest quadrant, with 303 stations, exhibits a broad curvilinear trend over the century with a broad local minimum from 1960 to 1980. The northwest quadrant, with just 143 stations, also has curvilinear trends similar to those for the southwest quadrant and has the largest year to year variation. The small size of long run rainfall stations in this quadrant limits the potential to extract stable statistics for the region.

While all four quadrants show generally similar temporal patterns, at least since the mid-1970s, the driving forces may not necessarily be the same. Thus, the northern part of the continent may be primarily attributable to lower activity of tropical cyclones, while the southern part may be attributable to both the increased frequency of frontal systems and the decreased frequency of storm events over southern Australia.

4.3. Seasonal features of spatial cross correlations

Nationwide averages of seasonal cross correlations of daily rainfall have remarkably similar long term trends to the annual ones shown in Figure 4. Winter and spring have slightly more consistent increasing trends than summer and autumn. Autumn shows the weakest increase in correlations at large distances. Berry et al. (2011a) reported that the seasonal variability of frontal frequency in Southern Hemisphere was much lower than that in Northern Hemisphere, which might partially explain the less variation of spatial cross correlations between seasons in this study.

5. CONCLUSIONS

This study investigated the spatial cross correlations of daily rainfall records from 2322 long run rainfall stations across Australia over the period 1910 to 2011 and assessed the long term trends in these correlations with respect to station separation, broad regional location and season. A substantial improvement in the quality of the daily rainfall records was done prior to the calculation of cross correlations. The key findings are:

a. There has been a steady strengthening in the spatial cross correlations of daily rainfalls in Australia since 1910, with most of this increase occurring after the mid-1970s. While this strengthening is naturally weaker with increasing Euclidean distance, it is consistently defined at distances up to 400-500 km. A strengthening of spatial cross correlation of daily rainfalls indicates an increase in the spatial consistency of daily rainfall events. This suggests an increase in the relative occurrence of broad scale rainfall such as frontal rainfall since the mid-1970s.
b. The strengthening in spatial cross correlation of daily rainfall since the mid-1970s appears to be consistent with the reported increase in the frequency of frontal rainfall systems and decrease of the frequency of storm events in Australia region. This suggests that the strengthening in spatial cross correlation is a useful indicator of broad scale changes in the climate system.
c. The strengthening of spatial cross correlations similar patterns in all four seasons, while the winter and spring showed more consistent trends.
d. The southeastern quadrant of the country had a stronger and more consistent strengthening of spatial cross correlation of daily rainfalls than other quadrants. All four quadrants show a substantial strengthening of the spatial cross correlation after the mid-1970s.
e. These findings are consistent with recent reported changes in synoptic scale climatic driving processes, especially the increasing frequency of frontal systems and the decreasing frequency of storm events in the Australian region.

This may help to assess how frontal systems change in the future climate and to quantify their likely impact around the globe (Berry et al. 2011b). In particular it could help to quantify the impact of climate change on Australian rainfall and to reduce the uncertainty in rainfall projections for the Australian region. This would support effective planning to address potential changes in the hydrological cycle at the regional and local level (Gallant et al. 2012; Klingaman 2012).

More work can be done to further improve the quality of the daily rainfall data with the aim of excluding any potential influences from the data quality issues, for instance, to narrow the time span for detecting the date shift errors and to develop methods to detect more sporadic errors in daily rainfall records.

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